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## TECHNICAL REPORTS

### Leaching of Atrazine in the Root Zone of an Alluvial Soil in Nebraska<sup>1</sup>

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#### ABSTRACT

Leaching of atrazine [2-chloro-4-(ethylamino)-6 (isopropylamino)-s-triazine] was measured from the soil surface to below the root zone in an irrigated field under continuous corn (*Zea mays* L.). The field was located in the Platte River Valley of central Nebraska in the central Great Plains area of the USA. This nearly level site is typical of the Platte River Valley with a coarse- to medium-textured soil of alluvial origin that contains low levels of organic matter, and with a water table at a 5-m depth. Vacuum soil water extractors located 1.5 m below the soil surface recovered an average of 0.072% of the atrazine applied to the surface during 1979 and 1980. Analysis of groundwater recovered from wells on opposite ends of the experimental field indicated enrichment with atrazine in the direction of the hydraulic gradient. Results support direct downward leaching as largely responsible for the low-level atrazine contamination detected in groundwater throughout the irrigated corn production areas of the valley.

**Additional Index Words:** groundwater, herbicide leaching, herbicide residue persistence, corn, nonpoint pollution.

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Atrazine [2-chloro-4-(ethylamino)-6 (isopropylamino)-s-triazine] is an herbicide used for the control of broad-leaf and some grassy weeds in corn (*Zea mays* L.) and sorghum [*Sorghum bicolor* (L.) Moench]. Atrazine was developed in 1953 and is now the most widely used agricultural pesticide in the USA (18). In 1978, 3.5 million kg were used in Nebraska (13). Atrazine inhibits photosynthetic electron transport between acceptor "Q" and plastoquinone. Resistant species (i.e., corn and

sorghum) have the ability to rapidly metabolize and thereby detoxify atrazine by *N*-dealkylation, 2-hydroxylation, and glutathione conjugation (2). The persistent nature of atrazine provides for season-long weed control; however, atrazine residues can persist in soil from one year to the next (3, 4, 26).

Atrazine is an integral part of crop production in the Great Plains, which often is essentially a monoculture of irrigated corn. However, recent technological advancements in sprinkler irrigation systems have allowed corn production to expand into more arid regions of the Great Plains, specifically the sometimes rolling, sandy-textured soils of the central Platte River Valley and the sandhills of Nebraska. Water pumped from shallow (1- to 6-m deep), unconfined aquifers that are alluvial deposits of coarse sand and gravel, is used for irrigation as well as for industry and domestic uses.

Recently, atrazine (up to 3 µg/L) has been identified in groundwater taken from aquifers underlying corn-growing areas of the central Platte River Valley (14). Laboratory and field studies (3, 9, 10, 25) conducted over the past 20 yr have shown that atrazine is adsorbed onto clay and soil organic colloids. However, in soils that lack appreciable amounts of these soil colloids, atrazine can easily be leached in spite of its limited solubility of 33 mg/L (21).

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Both empirical and/or theoretical approaches have been utilized to describe solute transport through soil. Oddson et al. (22) derived equations to describe the movement of organic chemicals through a soil profile, based upon physical considerations of mass flow and the energetic equilibrium that is assumed to exist between the adsorbed and soil solution fractions. They concluded that solutes would be transported as a "wave" through the profile. Rao et al. (24) developed a descriptive model for movement for solutes (either reactive and/or nonreactive) in soil resulting from water infiltration and redistribution. Model prediction of Cl<sup>-</sup> movement was in agreement with field observations. Likewise, a linear equilibrium between adsorption-desorption was assumed.

In these types of calculations, it is assumed that solute sorption behavior can be accurately described. It is generally assumed (although unproven) that a true dynamic equilibrium in the classical-chemical sense is established between solute in the adsorbed and solution phase, and that this behavior is constant (or at least predictable) across various concentrations and soil water contents. Wauchope and Koskinen (38), using thermodynamic considerations, calculated the energy changes associated with adsorption-desorption phenomena for several herbicides. Adsorption reduces the free energy of the herbicide in solution; moreover, this change was nearly identical for all herbicides evaluated. Results indicated that herbicides are passively adsorbed without specific bonding mechanisms.

Measurement of solute transport under natural conditions is generally achieved through lysimeters placed at predetermined depths, which serve to intercept flow of solutes. Jury et al. (15), using lysimeters placed 1.5 m below surface and salinity sensors at other depth increments, monitored salt transport in four soil types. Great variation in salt transport was measured in a lateral direction within a single experiment. Computer modeling of the process identified water uptake in the top 600 mm as having a much greater influence on transport than hydraulic conductivity of the media.

Two stable C isotopes, <sup>12</sup>C and <sup>13</sup>C, exist in nature at a concentration ratio of 91:1 (36). Plants that fix C via the C<sub>3</sub> pathway exhibit a greater preference to <sup>12</sup>C (to the exclusion of <sup>13</sup>C) than C<sub>4</sub> plants. This isotope selectivity results in a distinctly different <sup>13</sup>C/<sup>12</sup>C ratio between the two plant types. Spalding et al. (34), using mass spectrophotometric determinations of the <sup>13</sup>C/<sup>12</sup>C ratio, concluded that dissolved organic C within the atrazine-contaminated aquifer was derived from C<sub>4</sub> plants. Since corn is the predominant C<sub>4</sub> plant in the area, this research demonstrated that organic material may be leached from soil surface to underlying aquifers. Aquifers used in this study are also polluted with nitrates (32). Work of Linderman et al. (19) indicated downward leaching of N fertilizers, concomitant with aquifer recharge, as the predominate route of entry for NO<sub>3</sub><sup>-</sup> into groundwater.

Atrazine contamination of groundwater could arise from either point or nonpoint sources. Leaching of atrazine from surface irrigation tailwater reuse pits has been implicated as one possible point source of groundwater contamination (33). Since both organic materials derived from plant degradation and nitrates can be

leached from the soil surface to the groundwater, atrazine may likewise be leached into the aquifer during aquifer recharge. Observance of widespread low levels of atrazine contamination led Junk et al. (14) and Spalding et al. (35) to conclude that the herbicide was predominantly of nonpoint origin. However, no attempt has been made to quantify the leaching of atrazine below the root zone. The objective of this study was to verify the leachability of atrazine and to measure its downward movement in the root zone under normal agricultural production conditions.

## MATERIALS AND METHODS

To investigate the leaching of atrazine, a field site was selected that had been continuously cropped to corn and irrigated by either furrow or center-pivot systems. In 1973, eight vacuum extractors were buried 1.5 m below the soil surface in a field (Fig. 1) approximately 9.5 km south of the Platte River near Bellwood, NE. The vacuum extractors were used in previous studies to determine irrigation water efficiency and NO<sub>3</sub><sup>-</sup> leaching (19).

Vacuum extractors were 0.15 m wide, 3.25 m long, and 0.2 m deep. In cross section, each extractor had a "V"-shaped bottom with vertical sides. Ceramic candles, positioned in the base, extended the length of the extractors. Candles and collection reservoirs were kept under constant suction, and water in each extractor moved through the candles and into the reservoirs beneath each extractor. Vacuum on the candles was adjusted to approximately 0.1 bar tension. At that tension, water flow through the candles was rapid enough to remove free water from the extractors under high flow conditions, but not so great as to cause convergence of vertical flow of water towards the extractors. The soil was a Simeon loamy sand (mixed, mesic, Typic Ustipsamment), with 72, 17, and 11% sand, silt, and clay, respectively, in the surface 0.3 m. Percent sand increased with soil depth so that below 1 m the amount of silt and clay was negligible. The texture was medium to coarse sand with a higher percent of fine gravel as depth increased from bottom to root zone to water table. At field capacity, about 80 mm of water was available within a 1-m rooting depth. Surface soil pH was between 5.7 and 6.2 (19).

An observation well was established on both the east and west edge of the research field to obtain monthly groundwater samples (Fig. 1). Wells consisting of a 50-mm diameter steel pipe with a well point covered with 40-mesh screen were positioned outside the drawdown cone of the irrigation well and extended from 1 to 1.5 m into the

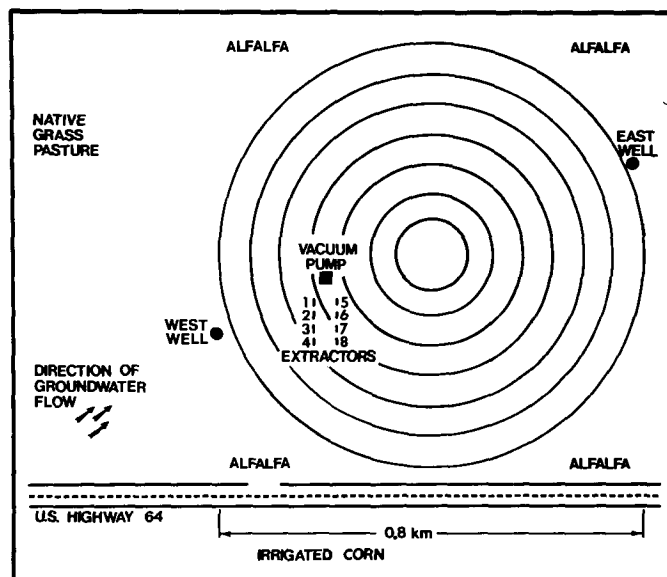


Fig. 1—Diagram of the center-pivot-irrigated field with vacuum soil water extractors 1.5 m below the surface of a Typic Ustipsamment loamy sand soil near Bellwood, NE.

aquifer. The water-sampling routine was to bail out 2 L of water standing in the well with a check-valve sampler before sampling the water for analysis. The north, south, and east sides of the test field were bordered by farms producing corn and cattle (*Bos* sp.). The west side of the field (upstream) was bordered by 3 km of native sod, which was used for grazing cattle without applications of pesticide or fertilizer for at least 15 yr. Groundwater flow was in an east-northeasterly direction; therefore, groundwater from the west observation well probably was representative of a pristine area. However, the well was immediately adjacent to the irrigated field and recharge from irrigation could at times provide a reverse gradient on the water table. The water table depth was about 5 m with a slight drawdown during the pump irrigation season. Atrazine was applied to the field by the grower at a rate of 2.2 kg/ha as part of his typical production practices on 21 May 1979. Additional atrazine was applied over the extractor site to give a total rate of 4.4 kg/ha (twice the normal rate). Potassium bromide (336 kg/ha as KBr) was applied at the same time to provide 225 kg/ha of Br<sup>-</sup> as a tracer of water percolation. During the 1980 growing season, atrazine was applied by the grower on 18 May at the normal use rate of 2.2 kg/ha (13); no additional atrazine or KBr was applied. The history of atrazine use on this field was unknown previous to this study; however, irrigated corn has been produced at this site for > 25 yr, and herbicide used for at least 10 yr. Extensive use of herbicides, including atrazine, has been common in the Platte River Valley for many years.

In 1979, the basic fertilizer application program was as follows: 9 kg N/ha as urea ammonium nitrate (UAN) on 10 May, 168 kg N/ha as anhydrous NH<sub>3</sub> knifed in on 13 June, and 64 kg N/ha as UAN applied with irrigation water through the center pivot on 10 July. Fertilizer applications in 1980 were: 31 kg N/ha as UAN on 18 May, and 179 kg N/ha as UAN applied with the irrigation water through the center pivot on 10 June. Each year an additional 112 kg N/ha as ammonium nitrate was broadcasted over four extractors (numbers 1, 4, 5, and 8) within 2 weeks of planting.

Water samples were collected from preplanting (mid-May) until past harvest (mid-September) in 1979 and 1980. Water collected in each extractor reservoir was sampled weekly, measured, and analyzed for atrazine, NO<sub>3</sub><sup>-</sup>-N (12), and Br<sup>-</sup> (1979 only) by colorimetric analysis (23). Atrazine analysis procedures (developed by authors) entailed carbon tetrachloride extraction, high-pressure liquid chromatography clean up, and qualitative and quantitative analysis with gas-liquid chromatography. Water spiked with atrazine (200 µg/L) indicated a recovery of 65% with a standard deviation of 5%. Concentrations of atrazine and Br<sup>-</sup> in 1979 were averaged for all extractors at each collection period. Concentrations of NO<sub>3</sub><sup>-</sup>-N were averaged for each set of four extractors that had received low (no additional N) and high (additional N applied) rates of N fertilizer. Total amount of atrazine and NO<sub>3</sub><sup>-</sup>-N recovered during each collection period was determined by multiplying the respective concentrations by the total volume of water recovered by the extractors. The seasonal amount (in kg/ha) was calculated based on the combined surface areas of the extractors.

A single soil core was taken immediately adjacent to each extractor to a depth of 1.8 m on 10 Apr. and 13 Nov. 1979 and again on 21 Apr. 1980. Soil cores were divided into depth increments of 0- to 0.15-, 0.15- to 0.30-, and 0.30-m increments from 0.30 to 1.80 m, and were analyzed separately for bulk density, soil texture (5), organic matter content (8), and atrazine content. Soil was first Soxhlet extracted with methanol, with the subsequent steps identical to those followed for water extracts. The atrazine adsorption coefficient ( $K_d$ —equilibrium ratio between absorbed and solution concentrations (20))—was also determined for each increment. Atrazine concentration data were analyzed as a factorial design of two dates by seven depths, with eight replications. Significant differences at the 5% level of probability were based upon a LSD test (31).

## RESULTS AND DISCUSSION

### Irrigation and Water Management

In 1979, the combined irrigation and precipitation during the growing season was 442 mm, of which about 9.5% (42 mm) was collected in the extractors (Table 1). This water was considered lost from the root zone, and would eventually be a source of aquifer recharge. The

**Table 1—Water, N, and atrazine applied and recovered by extractors during 1979 and 1980 in the Platte River Valley near Bellwood, NE.**

Applied to the soil surface	Time interval	
	19 May to 15 Sept. 1979	8 May to 16 Sept. 1980†
Water (mm)		
Irrigation	236.0	323.0
Rainfall	206.0	227.0
Total	442.0	550.0
Nitrogen (kg N/ha)		
Low rate	241.0	266.0
High rate	353.0	378.0
Atrazine (kg/ha)	4.4	2.2
Bromide, Br <sup>-</sup> (kg/ha)	225.0	--
Recovered in the Extractors		
Water (mm)	42 (9.5%)‡	46 (8.4%)
Nitrogen (kg N/ha)		
Low rate	10.0 (4.1%)	4.8 (1.8%)
High rate	16.7 (4.7%)	8.7 (2.3%)
Atrazine (mg/ha)	340 (0.0077%)	150 (0.0068%)
Bromide, Br <sup>-</sup> (kg/ha)	1.9 (0.84%)	--

† Vacuum extractors did not operate between 10 and 13 Aug. 1980, because percolation from precipitation of 93 mm 9–10 Aug. exceeded the capacity of the system. Amount actually leached was greater than the amount recovered in the extractors.

‡ Number in parentheses is the percentage of the total applied that was recovered in the extractors based upon a total extractor area of 3.9 m<sup>2</sup>.

1980 growing season was dry in May and July, and abnormally large amounts of irrigation water were required. Precipitation between 10 and 16 August, totaling 186 mm, produced the major portion of water that percolated below the root zone. Consequently, rate of water leached was more uniform in 1979 than in 1980 (Fig. 2A). Irrigation in 1980 resulted in slightly less loss to deep percolation—8.4% (46 mm) of water applied was recovered in the extractors in 1980 compared with 9.5% (42 mm) in 1979. By most standards used in irrigated agriculture, these amounts of leaching on a sandy soil represent highly efficient irrigation practices. Normal amounts of leaching could exceed these values by several times and would be even greater for furrow irrigation systems.

The concentration of Br<sup>-</sup> in the water recovered in the extractors peaked on 12 June 1979 and decreased rapidly thereafter. This indicated that sufficient water was applied to the field between 21 May and 12 June to leach Br<sup>-</sup> from surface to the 1.5-m depth.

### Leaching Patterns

Atrazine concentrations peaked at 2.2 µg/L on 18 July 1979, approximately 8 weeks after application (Fig. 2). It is not known if this atrazine peak concentration resulted from the 1979 application, but it is unlikely since the NO<sub>3</sub><sup>-</sup>-N recovered from either the high or low N rates did not follow the atrazine trend in general or respond differentially due to the N rates. In 1980, an initial peak in atrazine concentration (1.1 µg/L) occurred approximately 3 weeks after application, followed by a smaller second peak (0.5 µg/L) 8 weeks after application. Both peaks probably resulted from residual atrazine in the profile from the previous year, since NO<sub>3</sub><sup>-</sup>-N would be expected to leach to the extractors before atrazine.

Nitrate leaching data suggest the 1979 fertilizer N application did not reach the extractors until July at the

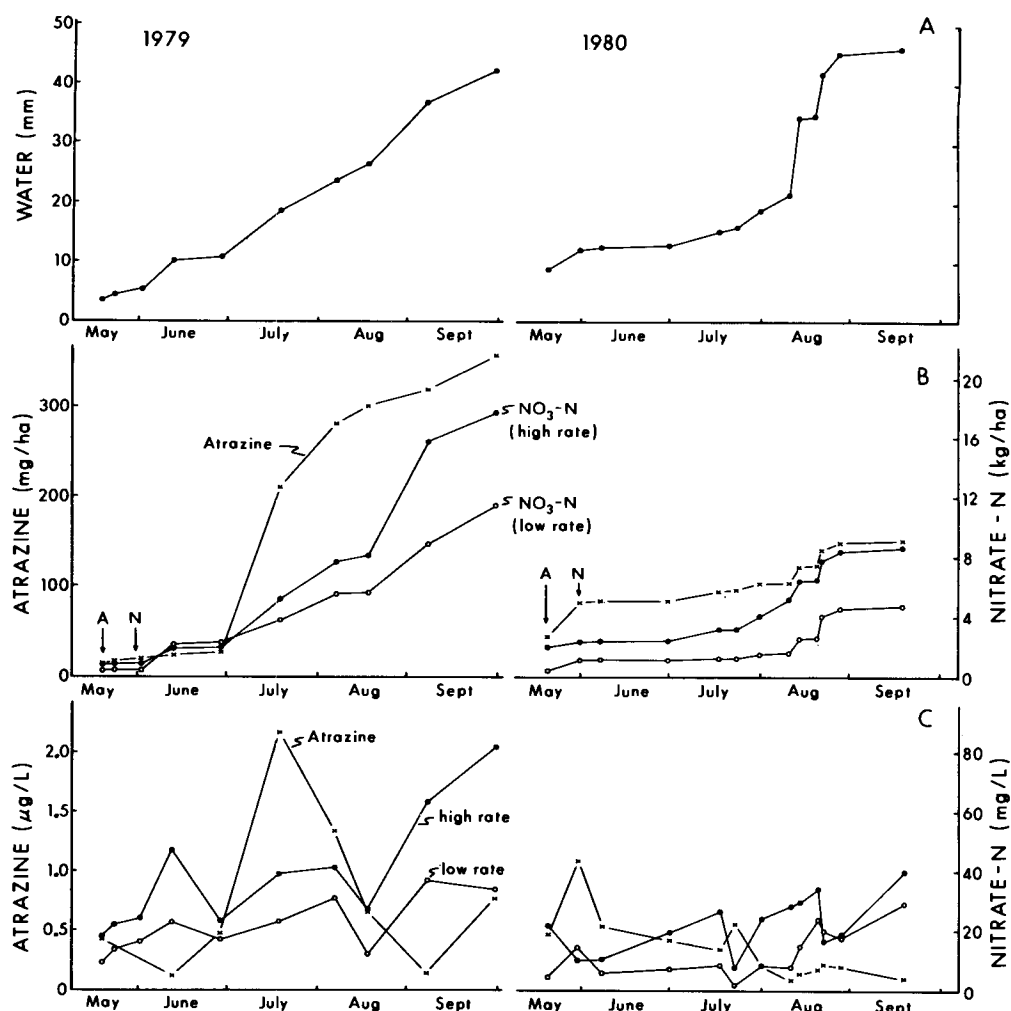


Fig. 2—Leaching patterns during the 1979 and 1980 growing season for irrigated corn near Bellwood, NE. (A) Cumulative water depth, (B) cumulative atrazine and nitrate-N, and (C) concentration of atrazine (A and N are times of atrazine and extra N application, respectively.)

earliest. At that time 10.7 mm of water had percolated to the extractors. Prior to that time,  $\text{NO}_3^-$ -N leached was similar in all extractors as would be expected since soil cores from spring of 1979 had similar levels of residual N. Soil cores taken in the fall of 1979 contained 224 and 186 kg/ha residual  $\text{NO}_3^-$ -N to a 1.8-m depth for the extractors receiving the high and low rate of N fertilizer, respectively. This greater residual soil N is also reflected by consistently greater  $\text{NO}_3^-$ -N leaching during 1980 for the higher N fertilizer rate. It is not known if the 1980 fertilizer N application reached the extractors before mid-September when the extraction was discontinued. Residual soil N in the fall of 1980 was 291 and 214 kg N/ha for the high and low N rates, respectively. These large residuals suggest the 1980 percolation was not sufficient to leach much N below the root zone; however, the  $\text{NO}_3^-$ -N concentration on the last sampling date suggests the 1980 applications may have just reached the extractors (Fig. 2). Percolation characteristics under field conditions with variable soil water conditions of the surface soil, amounts of applied water, and rate of application contribute to the observed leaching patterns. Some of the same observations have been made by Kay and Elrick (16) in the

laboratory under different flow rates. Since atrazine tagged with radioisotopes was not used in this study, differences in leaching patterns between high and low N rates are probably the best indicator of how soon after application material could reach the extractors. The most definitive evidence from this study was obtained in 1978 when leaching from the high rate of N application began to markedly exceed the low rate in mid-July after 65 mm of percolation and 50 d after application (28).

Lack of uniform percolation in 1980 probably accounts for dissimilarity in the leaching pattern between the 2 yr. The peaks in concentration observed in both years suggest that atrazine was leached through the profile toward the water table in a "wave-like" or "pulse" manner.

Three separate peaks in  $\text{NO}_3^-$ -N concentration were evident during the 1979 growing season, corresponding to the three separate applications of N fertilizer. Flatness of the second  $\text{NO}_3^-$  peak may have resulted from the fact that most of the N fertilizer was applied as  $\text{NH}_3$ , which had to be nitrified before being leached. Less water movement and nonuniform leaching in 1980, compared with 1979, may also account for the less distinct concentration peaks observed for nitrates in

Table 2—Concentration of atrazine and Br<sup>-</sup> in soil cores adjacent to the vacuum extractors in November 1979 and April 1980 at Bellwood, NE.

Soil depth m	Soil texture	Organic matter %	Atrazine adsorption coefficient K <sub>d</sub>	Bulk density Mg/m <sup>3</sup>	Bromide, Br <sup>-</sup> mg/kg	Atrazine concentration			
						Nov. 1979		Apr. 1980	
						μg/kg	g/ha†	μg/kg	g/ha†
0-0.15	Sandy loam	1.7	0.60	1.78	2.3	7.77	20.5	5.06	13.5
0.15-0.30	Sandy loam	1.7	0.60	1.78	1.4	7.60	20.3	3.25	8.7
0.30-0.60	Sandy loam	1.7	0.60	1.78	1.4	5.27	28.1	1.46	7.8
0.60-0.90	Loamy sand	0.3	0.46	1.72	0.9	1.91	10.2	1.38	7.4
0.90-1.20	Sand	0.1	0.45	1.45	1.1	0.86	3.8	0.44	1.9
1.20-1.50	Sand	0.1	0.45	1.45	0.5	0.66	2.9	0.38	1.7
1.50-1.80	Sand	0.1	0.45	1.45	1.1	0.20	5.3	0.26	1.5
Average concentration					1.2	3.47		1.75	
LSD 0.05 =					0.6	2.91		2.91	
Total residue							91.1		42.5

† Total residue in each increment of depth as determined from the respective bulk density and atrazine concentration.

1980. During the 1979 growing season, extractors recovered 10.0 kg NO<sub>3</sub><sup>-</sup>-N per ha (or 4.1% of the amount of fertilizer applied) from the plots that received the lower application rate of fertilizer (241 kg N/ha) (Table 1). Nitrate-N recovered in the extractors that received the higher rate of N fertilizer (353 kg/ha) totaled 16.7 kg/ha (or 4.7% of the amount applied). During the same period, Br<sup>-</sup> equivalent to 1.9 kg/ha (about 1% of amount applied) was recovered in the water. Concentrations in the soil ranged from 2.3 mg/kg in surface layer to 0.5 mg/kg in the 1.2- to 1.5-m depth (Table 2). Total amount of Br<sup>-</sup> in measured portion of soil profile was equivalent to 30.7 kg/ha or 14% of the amount applied. The portion unaccounted for was probably taken up by the irrigated corn crop.

Total amounts of atrazine recovered by the extractors during the 1979 and 1980 growing seasons were equivalent to 340 and 150 mg/ha, respectively (Table 1). The fact that atrazine had been applied at unknown rates to this site prior to initiation of this experiment makes attempting to construct a budget for the atrazine we applied very speculative. However, if it was assumed that the atrazine recovered in the extractors during the growing season was predominantly derived from that year's application, the amounts recovered represent 0.0077 and 0.0068% of the amounts applied in 1979 and 1980, respectively. The mathematical model for predicting herbicide movement in soil by Rao et al. (24) should relate to this situation. According to their model, the amount of water, *I*, in centimeters, needed to piston-displace a solute from the surface to the 1.5-m depth would be calculated as:

$$I = 150 \theta_{FC} R, \quad [1]$$

where  $\theta_{FC}$  is the average soil water content, 0.08 m<sup>3</sup>/m<sup>3</sup>, and *R* is the solute retention factor. The retention factor is defined as:

$$R = 1 + (\rho_B K_d / \theta_{FC}), \quad [2]$$

where  $\rho_B$  is soil bulk density (1.6 mg/m<sup>3</sup> from Table 2) and *K<sub>d</sub>* is solute adsorption coefficient, which is 0.5 for atrazine and 0 for Br<sup>-</sup>. Calculated *R* for atrazine and Br<sup>-</sup> are 11 and 1, respectively. Therefore, based on these calculations, the amount of water needed to displace atra-

zine and Br<sup>-</sup> through 1.5 m of soil would be 1.32 and 0.12 m, respectively. The calculated value required to leach atrazine 1.5 m was much greater than the seasonal values measured. It is therefore concluded that the atrazine found in the extractor was probably applied previous to that crop year.

Criticism often arises in lysimeter work as to whether or not distinct regions of high or low amounts of leaching occurred (i.e., "fingering"), making the limited area measured by the lysimeter unrepresentative. Years of field data from this site show that the extractors are responsive to soil water conditions and have proven to be a good technique to measure effects of water and fertilizer management (19, 28). The authors suggest that the technique described herein is one of the best available for measuring water movement in the field. Occasionally, the amount of leachate from an individual extractor was too small a volume for the desired analysis; consequently, leachate from all extractors was combined. However, for several sample periods, leachate volume was adequate to permit analysis from individual extractors. Atrazine concentrations were comparatively uniform with generally less than twofold difference between extractors.

Atrazine degradation can occur by either microbial or chemical means. Microbial degradation results in *N*-dealkylation to produce deethylated atrazine and/or deisopropylated atrazine. Chemical degradation is characterized as a hydrolysis reaction at the number two carbon to produce hydroxyatrazine (2, 17, 27). Microbial degradation is temperature-dependent and parallels the presence of additional C and energy sources (29). Microbial degradation has been shown to be minor compared with chemical hydrolysis, especially at pH levels < 6 (27, 30). Adsorption onto soil colloids is a prerequisite for hydrolysis (1).

Previous research has focused on atrazine degradation in the plow layer; consequently, little information is available on degradation in subsoil layers. Roeth et al. (26) found that degradation in the subsoil proceeded at one-third the rate of that in surface soil. A similar conclusion was reached by Harris et al. (11). Goswami and Green (7) detected atrazine degradation to hydroxyatrazine under anaerobic conditions of rice (*Oryza sativa* L.) paddies. It remains unknown whether microbial and/or chemical hydrolysis can occur. Our research on atrazine

degradation (to be published elsewhere) under simulated aquifer conditions (saturated aquifer sand, 12°C, pH = 6.2) indicated that hydroxyatrazine would be produced at a rate of 3% every 90 d. Even under conditions more conducive to microbial activity (additional sources of C, 24°C, and aeration), results were unchanged. Consequently, we conclude that conversion of atrazine to hydroxyatrazine is the only means of degradation within the aquifer.

### Groundwater

The water table at this site remained at 4.3 m below the soil surface during the winter months, and dropped to about 6.0 m during the latter part of the irrigation season; it was approximately 0.8 m lower on the down gradient east side of the field. This height differential reached a temporary maximum of 1.5 m during the irrigation season. Based upon an average water table differential across the field of 0.8 m, the Darcian groundwater flow equation (6) indicates an easterly flow at a velocity of 0.4 m/d; however, the natural flow would be accelerated during irrigation in the cone of depression of the well.

Groundwater from the west well contained an average of 0.14 µg/L atrazine during the observation period, while the east well contained 0.87 µg/L. The presence of atrazine in the west well could be accounted for by atrazine applied to the irrigated field associated with temporary reversals in groundwater flow directions due to recharge from irrigation. Wehtje et al. (39) found similar range in concentration in groundwater from a different part of the Platte River Valley. Increase in atrazine concentration in the direction of flow indicates enrichment as a result of passage under the field. The sharp rise in concentration during the late summer months is seen in both years and with both wells (Fig.

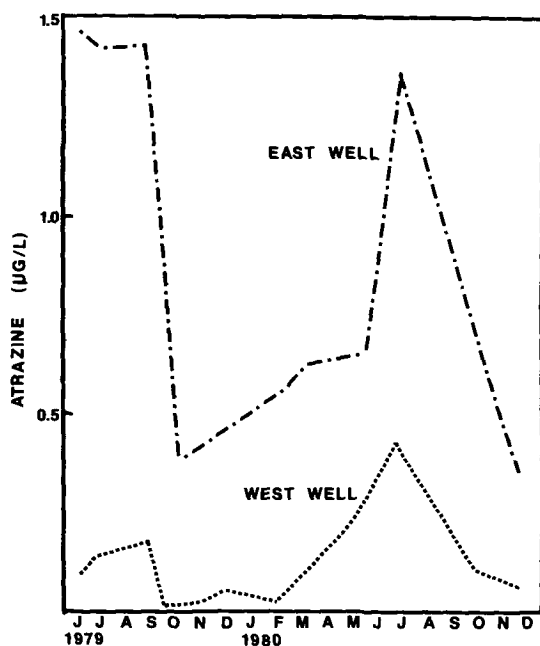


Fig. 3—Concentration of atrazine in groundwater recovered from observation wells during the 1979 and 1980 growing seasons at Bellwood, NE.

3). Assuming that 0.0072% of the recommended rate of atrazine applied during a single season (158 mg/ha) was to be deposited and dispersed into the surface 0.3 m of the aquifer, with 50% pore space, a concentration of 0.105 µg/L would result. This value is lower but not unreasonably different from that actually measured. Furthermore, the concentrations in the groundwater reflect repeated cycles of application, leaching, and eventual deposition without complete dissipation.

### Soil Profile

Atrazine was detected in all depth increments of the soil profile, but concentration was least in the deepest increment (1.5–1.8 m) for fall 1979 and spring 1980 (Table 2). A considerable drop in concentration was detected between the surface horizon and the lower depths of the profile. There were no significant differences in atrazine concentration in the bottom four increments (0.6–1.8 m) of cores taken in November 1979 and the bottom five increments (0.3–1.8 m) in April 1980. The  $K_d$  of the bottom four increments were nearly identical, indicating that very few soil colloids exist below 0.6 m to bind atrazine and impede further downward leaching. The substantial drop in organic matter content between 0.3 and 0.6 m and 0.6 and 0.9 m agrees with this observation. Between November 1979 and April 1980, or 150 and 330 d after atrazine application, average concentration of atrazine in the soil dropped from 3.47 µg/kg (91.1 g/ha) to 1.75 µg/kg (42.5 g/ha). This dissipation of atrazine may be attributed to (i) chemical degradation by hydrolysis and (ii) downward leaching below the sampling zone.

Agricultural usage of atrazine results in only a small percentage of the amount applied leaching into the subsoil. Since the soil medium between the extractors (1.5 m) and the aquifers (4–5 m) is almost pure sand, there is nothing to prevent further downward leaching of these “pulses” and eventual deposition into the aquifer. Attempting to mathematically predict when a particular pulse will enter the aquifer is prevented by the lack of uniformity over time of the leaching process and variable water content of the nonsaturated zone above the aquifer. However, since atrazine has been applied in the valley for many years, pulses are probably entering the groundwater at approximately annual intervals, although  $\geq 1$  yr may elapse between application and entry of the resulting pulse into the aquifer.

The amount of atrazine that reaches the aquifer is small. Approximately 0.007% of the atrazine applied annually was leached to a depth of 1.5 m, with 9% of the applied water going to deep percolation and probable aquifer recharge. Degradation during the remainder of the leaching period would reduce this amount slightly.

In general, this location is representative of a large portion of the central Platte River Valley in terms of soil texture, structure, and depth to water table. Consequently, these results are a reasonable estimate of the leachability of atrazine for a sandy soil under center-pivot irrigation. Much of the corn production in the central Platte River Valley is furrow irrigated, which makes water management more difficult and is less ef-

ficient in preventing deep water percolation than is sprinkler irrigation (37). Linderman et al. (19) monitored water loss from deep percolation for furrow irrigation at this field site prior to conversion to a center-pivot system. With furrow irrigation, deep percolation accounted for up to 25% of all water available between corn planting and harvest. A 25% water loss might result in approximately 0.020% of the applied atrazine leaching into the subsoil, assuming that the relationship between deep percolation and the amount of atrazine leached is linear. Because average atrazine application rate in this area is 1.6 kg/ha (13), the amount of atrazine lost by deep leaching would be approximately 0.12 g/ha under center-pivot irrigation. Under furrow irrigation, atrazine leaching could approach 0.32 g/ha.

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